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ABSTRACT

The Fermilab Main Injector is a new 150 GeV proton synchrotron, designed to replace the Main Ring and improve the high energy physics potential of Fermilab. The status of the Fermilab accelerator complex upgrade will be discussed. Study of the stability of the beam in the Main injector will be discussed. Detuning and corrector scheme to improve the dynamic aperture of the Main Injector will presented. Tune modulation caused by octupolar detuning will be discussed.

1. Introduction

The Fermilab Tevatron is the highest energy proton-antiproton collider in the world today and it will remain so until either the Superconducting Super Collider (SSC) or Large Hadron Collider (LHC) is operational. At present Fermilab accelerator complex is in the middle of an upgrade plan FERMILAB III. This upgrade plan will slowly increase the luminosity in the Tevatron by at least a factor of thirty. Major components of this upgrade plan are installation of electrostatic separators in the Tevatron, installation of low β systems at the two collider detectors located at B0 and D0, antiproton source improvements, upgrading the linac energy from 200 MeV to 400 MeV, installation of cold compressors and fast kickers and the construction of a new accelerator, the Fermilab Main Injector.

This upgrade plan is designed to extend the discovery potential of the U.S. High Energy Physics program. Some of the physics goals of Fermilab III are to discover and study the properties of the top quark, the last unobserved fundamental particle; to provide a factor of two increase in the mass scales characterizing possible extensions to the Standard Model; high rate b-quark hadron production and decay experiments, perhaps leading to the study of CP violation in b-quark hadron, and to support new initiatives in the neutral kaon physics and neutrino oscillation investigations.

2. Status of Upgrades

At present, Fermilab is under collider operation Run 1a. This run is underway after the successful installation of electrostatic separators in the Tevatron. These separators create helically separated orbits in the Tevatron and keep proton and antiproton bunches separated everywhere except at the two collider detectors. Significant improvements have been made to the Antiproton source to increase the accumulation rate and reduce the emittance of a given stack size. During this run Fermilab has been making record in antiproton stacking. The new low β system is operational and has allowed the implementation of a second high luminosity interaction region. At present the Tevatron is running at a luminosity larger than 4.5×10^{30} and is slowly heading towards the goal of 6×10^{30}.

After this run, the linac upgrade will be completed by replacing the second half of the existing drift tube linac with a side coupled structure generating about 300 MeV in the same length. This increase in energy will improve the injection into the 8 GeV Booster due to the reduction in space-charge forces. This will also increase the proton transverse beam densities and will benefit antiproton production by increasing the proton flux through the Main Ring. Before the Main Injector, cold compressors and fast kickers will be installed in the Tevatron to increase the beam energy from 900 GeV to 1000 GeV and number of bunches from 6 to 36. These upgrades will provide at least a factor of two increase over current luminosity.

3. The Main Injector

The Fermilab Main Injector (FMI) is a new 150 GeV proton synchrotron designed to remove the limitations of the Main Ring in the delivery of high intensity proton and antiproton beams to the Tevatron and to increase the antiproton production rate. The Main Ring normalized aperture (12π mm-mr) is about half the size of the current booster aperture. After the 400 MeV linac upgrade the booster aperture will increase to about 30π mm-mr. The FMI is designed to have a transverse aperture of 40π mm-mr . The FMI will increase the number of protons targeted for antiproton production from $3.2 \times 10^{15}/hour$ to $1.2 \times 10^{16}/hour$ and will be capable of efficiently accelerating antiprotons from larger stacks containing 2×10^{12} antiprotons for injection into the Tevatron collider. It will also increase the total number of protons which can be delivered to Tevatron to 6×10^{13}, and deliver proton bunches containing up to 3×10^{11} protons. The FMI will be capable of supporting a luminosity of 5×10^{31} in the existing collider. A new added feature due to FMI will be intense slow extracted beams, 3×10^{13} protons every 2.9 sec with 33% duty factor, for use in the studies of CP violation and rare Kaon decays, and for experiments designed to search for neutrino oscillations. In a similar amount of running time with FMI, a state of the art Kaon experiment will improve the upper limits of rare decays by two orders of magnitude.

The FMI will be constructed using a newly designed conventional dipole magnets. The new dipole magnets are being build based on considerations of field quality , aperture and reliability. The FMI lattice has two different types of cells, the normal FODO cells in the arcs and straight sections and the dispersion- suppressor FODO cells adjacent to the straight sections to reduce the dispersion to zero in the straight sections. There are eight straight sections, at present four are being used for beam transfer and one for radio frequency (rf) cavities.

Two full scale prototypes of the FMI dipoles have been built and undergone an extensive measurements of their field quality[1]. Measurements show that these magnets meet the designed specifications and are well described by the computer models. In the FMI we have two different length dipole magnets 6m and 4m. Several iterations of the dipole end design have been made to reduce the change in the effective length of the magnet and the sextupole component of the dipole ends. The change in the effective length introduces closed orbit error[2]. We have also initiated a dipole power supply R&D program. The power supply and magnet systems are designed to allow a significant increase in the number of 120 GeV acceleration cycles for simultaneous operation of antiproton production and 120 GeV slow spill beam. Besides the newly constructed dipoles, FMI will use existing components including quadrupoles, and 18 rf systems from the Main Ring.

4. Accelerator Physics

Accelerator physics studies are underway to understand the FMI better and also to improve its performance. These studies include incorporation of magnetic measurements into tracking studies, transition crossing studies, impedance budgeting, beam line design and study of slow extraction. Using the measurements of the two prototype dipoles, Main Ring dipoles and quadrupoles and PE2D static field calculations we have made a database for the systematic and random errors of FMI magnets[3]. This database is used in simulations of the dynamical performance of the FMI[4] and other studies such as power supply requirements, corrector strength etc.

Simulations to study the performance of the Main Injector at the injection energy of 8.9 GeV are described in this paper. We present a detailed study of the Main Injector lattice including the closed orbit errors, betatron function errors, tune versus amplitude, and dynamic aperture. The tracking calculations include the magnetic field errors, both systematic and random, and misalignment errors. In this paper we will briefly describe these errors along with the tracking conditions. A detailed description of these errors and their calculation can be found in MI66[1]. A thin element tracking program TEAPOT[5] has been used for these simulations.

Tracking Conditions and Errors

The Main Injector lattice has two different sizes dipole magnets, there magnetic lengths are 6.096 and 4.064 meters at 120 GeV. The magnetic length of these dipoles decreases with energies due to the saturation of ends, and at 8.9 GeV their length is 2.5 mm larger than the nominal at 120 GeV. This change in length introduces a non zero dipole multipole at each end of the magnet, and is represented in TEAPOT by a horizontal kick given by

$$H_{kick} = (\Delta L/2L_{ref}) * (2\pi/904/3) \qquad \text{radian}$$

Where ΔL is 2.5 mm. This additional bending of the particle, is corrected by decreasing the dipole excitation, calculated by eq-(14) of Ref. 3.

The ends of the magnet have different magnetic multipoles than the body of the magnet. Further the two ends of the dipole are slightly different due the presence or absence of nearby bus work, leading to the labels "BUS END" or "NO BUS END". For the tracking calculation the two ends and the body are treated as a separate magnets . The end multipoles, both normal and skew, are calculated by using the method described in the section 2.2 of Ref. 3. The multipoles used for these calculations were calculated by using the measurements where the 80" rotating coil was placed 50" inside the magnet rather than 30" as described in Ref. 3. This change gives us more consistent results at all the energies. These values are also in better agreement with the fit to the flat coil data between -1" to +1" in x. Multipole error values quoted for the dipole ends in Table 1 are obtained by dividing the integrated multipole moments by eight, (the length of a long dipole magnet 240" divided by 30"), so that their values can be directly compared with the dipole body multipole errors. The random errors of the body multipoles are calculated by using the measurements of the B2 dipoles at 210 Amps.

The values of the systematic and random errors of the quadrupoles are calculated using the Main Ring quadrupole measurements. There are a very limited number of measurements available for MR Quads. Normal multipoles are calculated by using the 195 Amps measurements, whereas the skew multipoles are calculated using the measurements at 1575 Amps. The variation of the octopole strength and random errors with current are small.

All skew quadrupole field errors are turned off, for the convenience of the simulation. Using a coupling compensation scheme any linear coupling effects due to the presence of skew quadrupole can be removed.

Table 1 summarizes all of the multipoles as used in the input file to TEAPOT. Multipole field errors are quoted in units of 10^{-4} at a displacement of one inch.

The misalignment of all the magnetic elements and beam position monitors has been included in this calculation. The sigma of the alignment error with respect to the closed orbit is 0.25 mm in both horizontal and vertical directions. In addition dipole magnets have a roll angle of 0.5 mrad sigma.

Base tune of (Q_x, Q_y) = (26.425, 25.415) were used in all the simulations. This tune is different than (26.407, 25.409) which was used for the Main Injector calculations before. This change in tune was necessary to increase the dynamic aperture, with all magnetic and misalignement errors turned on, the presence of an RF, and with chromaticity adjusted to -5,-5. In the lattice there are 18 RF cavities, each operating at $V_{rf} = 0.0218$ MV. The RF frequency is set to 54 MHz corresponding to a harmonic number of 588.

Closed orbit errors and Corrector strength

In the Main Injector lattice there are 208 quadrupoles. Located inside these quadrupoles are the beam position monitors. The vertical and horizontal beam position are measured at the focusing and defocusing quadrupoles respectively. The vertical and horizontal displacement of the particles are corrected by applying corresponding kicks just after these position monitors.

A typical uncorrected closed orbit in both the horizontal and vertical plane is shown in Fig 1. The average RMS closed orbit deviation before correction is 7.2 mm horizontal and 5.2 mm vertical for the selected seed. After three iterations of the orbit corrections the average RMS closed orbit deviation is reduced to 0.12 mm (H) and 8×10^{-3} mm (V).

We have studied the contribution of each magnetic errors and the displacement error to the average RMS closed orbit deviation for this seed. The total error is not a simple combination of all of these errors. There are some cancellation between errors. The result is summarized in Table - 2. Most of the orbit deviation is due to random errors . Fig 2 shows the distribution of uncorrected horizontal and vertical RMS closed orbit errors for 20 different seeds. The average RMS deviation of each seed is 7 mm and 6 mm in the horizontal and vertical planes respectively. The maximum corrector strength required to correct these orbit deviations is 150 *μradians* in both planes. In the Main Injector we plan to use recycled Main Ring dipole correctors and also use newly build dipole correctors. At 8.9 GeV the Main Ring dipole correctors can provide 570 μ radian and 350 μ radian of horizontal and vertical corrections respectively. The new correctors will be stronger, which will help correct the orbit at higher energy.

Tune versus amplitude and dynamical aperture results

We have studied the survival of particles launched at different amplitudes in the Main Injector at the injection energy. A single particle will go around 35000 turns at the injection energy of 8.9 GeV during any operation that involves filling the ring with six Booster bunches. A particle is launched with a maximum horizontal displacement of equal to "A" at a location where the horizontal beta function is at its maximum of 80 meters. The maximum vertical displacement of the same particle is 0.4A (x/y=2.5) also at beta of 80 meters. Synchroton oscillation were included in the simulation by launching all particles with an amplitude of $\delta_{max} = (\Delta p/p)_{max} = 2.0 \times E-3$.

Fig. 3 shows the variation of horizontal and vertical tunes as the amplitudes of the motion was increased. The numbers on the tune plot correspond to the initial amplitude "A" of a test particle, in millimeters. Points on the plot lie on a straight line up to an amplitude of about 17 mm, with the spacing between points increasing linearly. Both the horizontal and vertical tunes depend quadratically on amplitude, for moderate amplitudes. This octupolar detuning is dominated by a combination of the systematic octupole error in the recycled Main Ring quadrupoles, and second order sextupole effects.

Particles were launched from 1 mm to 25 mm amplitude. Particles with an amplitude above 19 mm did not survive for the full 35000 turns of the simulation, for this particular seed. Similar simulations were performed for five different seeds. Fig 6 is a survival plot, displaying how many turns a particle survives the 35k turns in the Main Injector, as a function of initial amplitude. If the dynamical aperture of the machine is defined as the smallest amplitude particle that did not survive for 35000 turns, then the dynamical aperture for the Main Injector at the injection energy is predicted to be 22 ± 1.4 mm, corresponding to a normalized emittance of $59.2 \pm 10.2\pi$ mm mradians.

To study the discussed detuning effects we have varied the octupole strength of the Main Ring quadrupole and sextupole strength of the Main Injector dipole ends. Reducing the end sextupole to half the nominal value has no significant effect on the quadratic detuning. Also there was no change to the dynamic aperture of the machine. When we set the octupole (b_3) component of the quadrupole to zero, the detuning is very small. Fig. 7 is a tune-tune plot for different initial amplitudes with half nominal sextupole strength of the dipole ends and $b_3 = 0$ for the MR quads. This study was done for only one seed. For this seed with nominal MR quads octupole particles with amplitude larger than 19 mm did not survive. Particles with amplitude larger than 24 mm did not survive when we set the $b_3 = 0$ for the MR quads. We are in process of developing a correction scheme, using the octupole correctors placed in the ring for 120 GeV slow extraction, to cancel or reduce the total octupole of the ring at 8.9 GeV. This will help us improve the dynamic aperture of the MI. We can improve this further by utilizing a quadrupole shuffling scheme, which will help to reduce the effect of quadrupole random error. Study of the FMI dynamical performance at 120 GeV and simulation of slow extraction is in progress.

The FMI has approval to begin the Title II work, below and above grade construction at MI-60 straight section, where rf will be located. We are requesting approvals for copper coil, steel lamination and to start general site preparation. The scheduled completion date and commencement of operations is 1997.

1. D. J. Harding *et al.*, "Design considerations and prototype performance of the Fermilab Main Injector dipole", *Proc. of the 1991 IEEE Particle Accelerator Conf.*
2. C. S. Mishra , H. D. Glass and F. A. Harfoush, "Effective length of the Main Injector Dipole and its effect on the Main Injector", *FMI Internal Report 0072.*
3. F. A. Harfoush and C. S. Mishra, "Systematic and Random errors for the Main Injector Tracking", *FMI Internal Report 0066.*
4. C. S. Mishra and F. A. Harfoush, "Simulation of the dynamical performance of the Main Injector at 8.9 GeV", *FMI Internal Report 0070.*
5. L. Schachinger and R. Talman, Particle Acc. 22,35 (1987)

Table 1

Magnetic errors used in the 8.9 GeV simulation

	Multipole order	Normal $< b_n >$	σb_n	Skew $< a_n >$	σa_n
Dipole Body	dipole	-4.68	10.0	-	-
	quadrupole	-0.13	0.45	-	-
	sextupole	0.43	0.61	-0.04	0.22
	8	0.09	0.13	0.00	0.41
	10	0.18	0.32	0.03	0.15
	12	-0.03	0.10	0.00	0.19
	14	-0.01	0.23	-0.05	0.08
Dipole end BUS	Dipole	2.05	-	0.0	-
	quadrupole	0.03	-	-	-
	sextupole	0.92	-	0.03	-
	8	-0.02	-	0.02	-
	10	-0.09	-	0.04	-
	12	0.04	-	-0.03	-
	14	-0.07	-	0.00	-
Dipole end NO BUS	Dipole	2.05	-	0.0	-
	quadrupole	0.03	-	-	-
	sextupole	0.99	-	-0.07	-
	8	-0.08	-	-0.02	-
	10	-0.11	-	-0.05	-
	12	-0.06	-	0.03	-
	14	-0.09	-	0.00	-
Recycled new Main Ring quadrupole	quadrupole	-	24.0	-	-
	sextupole	0.50	2.73	0.12	1.85
	8	5.85	1.02	-1.16	2.38
	10	-0.10	1.12	0.42	0.47
	12	-1.82	0.63	0.40	0.70
	14	0.21	0.64	-0.55	0.44
	16	1.41	0.64	-	-
	18	-0.03	0.12	0.14	0.16
	20	-0.80	0.06	0.02	0.07
Newly Built Main Injector quads	quadrupole	-	24.0	-	-
	sextupole	-	2.73	-	-
	8	-0.39	1.02	-	-
	10	-	1.12	-	-
	12	-1.39	0.63	-	-
	14	-	0.64	-	-
	16	1.29	0.64	-	-
	18	-	0.12	-	-
	20	-0.73	0.06	-	-

Table 2

Close Orbit Errors for one seed

Errors	Plane	RMS Diviation mm
All	H	6.3
	V	4.3
Dipole systematic (including ΔL)	H	1.1
	V	0.0
Dipole Random	H	5.1
	V	0
Quad Systematic	H	0.
	V	0.
Quad Random	H	0.
	V	0.
Displacement and Rotational Error	H	2.6
	V	4.2
Change of effective length	H	1.1
	V	0.

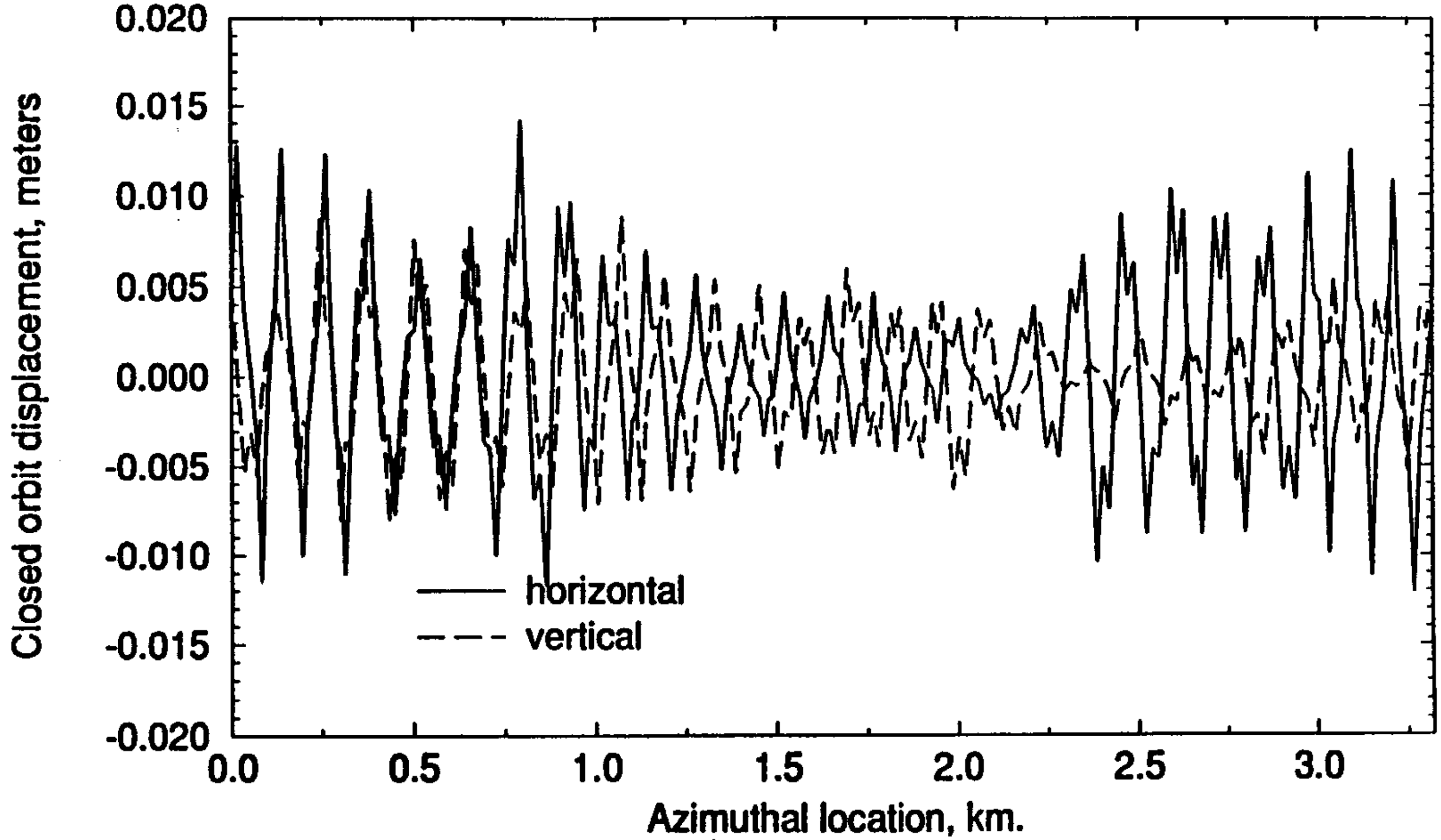

Fig. 1 Closed orbit errors before correction

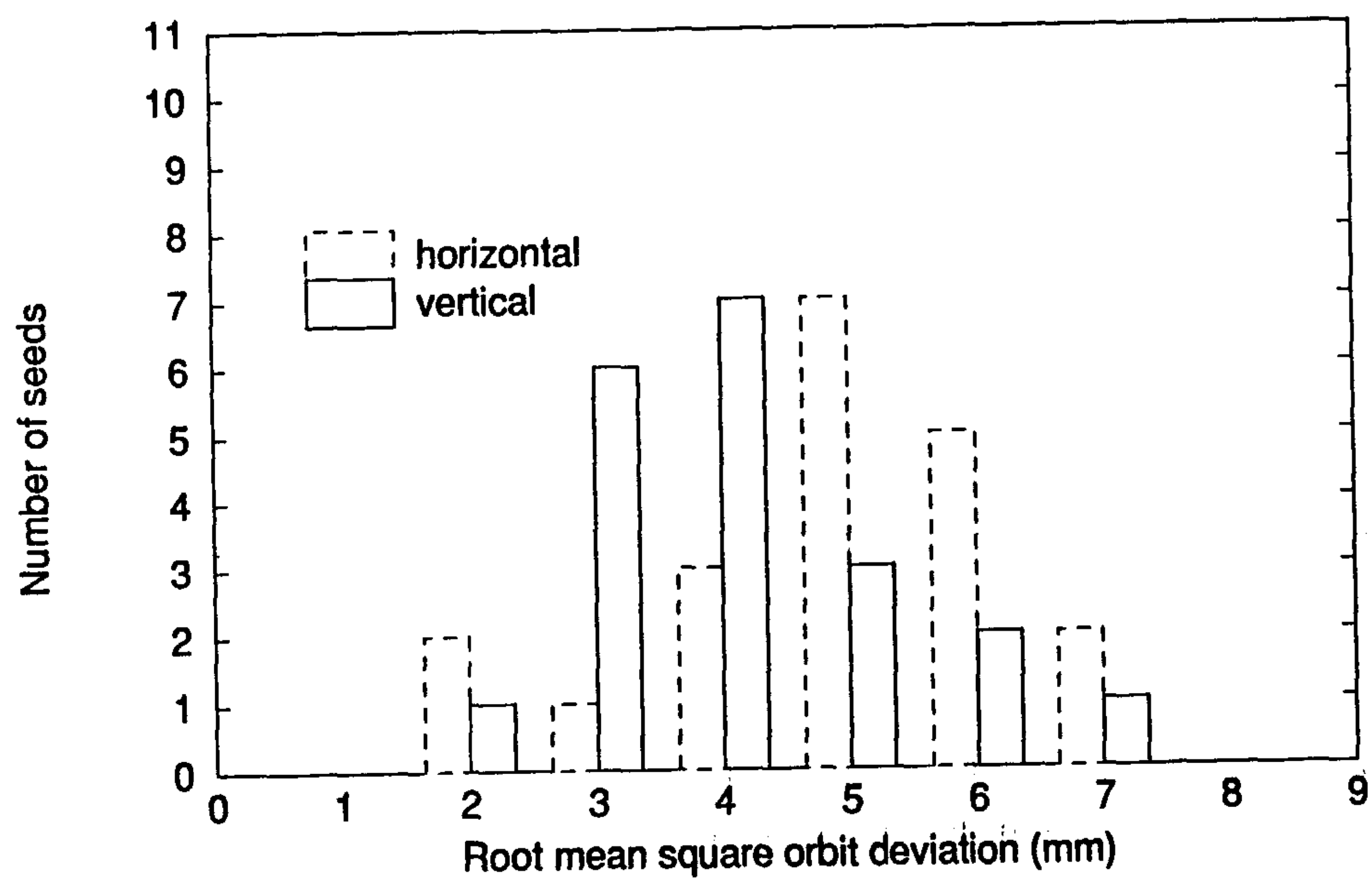

Fig. 2 Histogram of closed orbit errors before correction

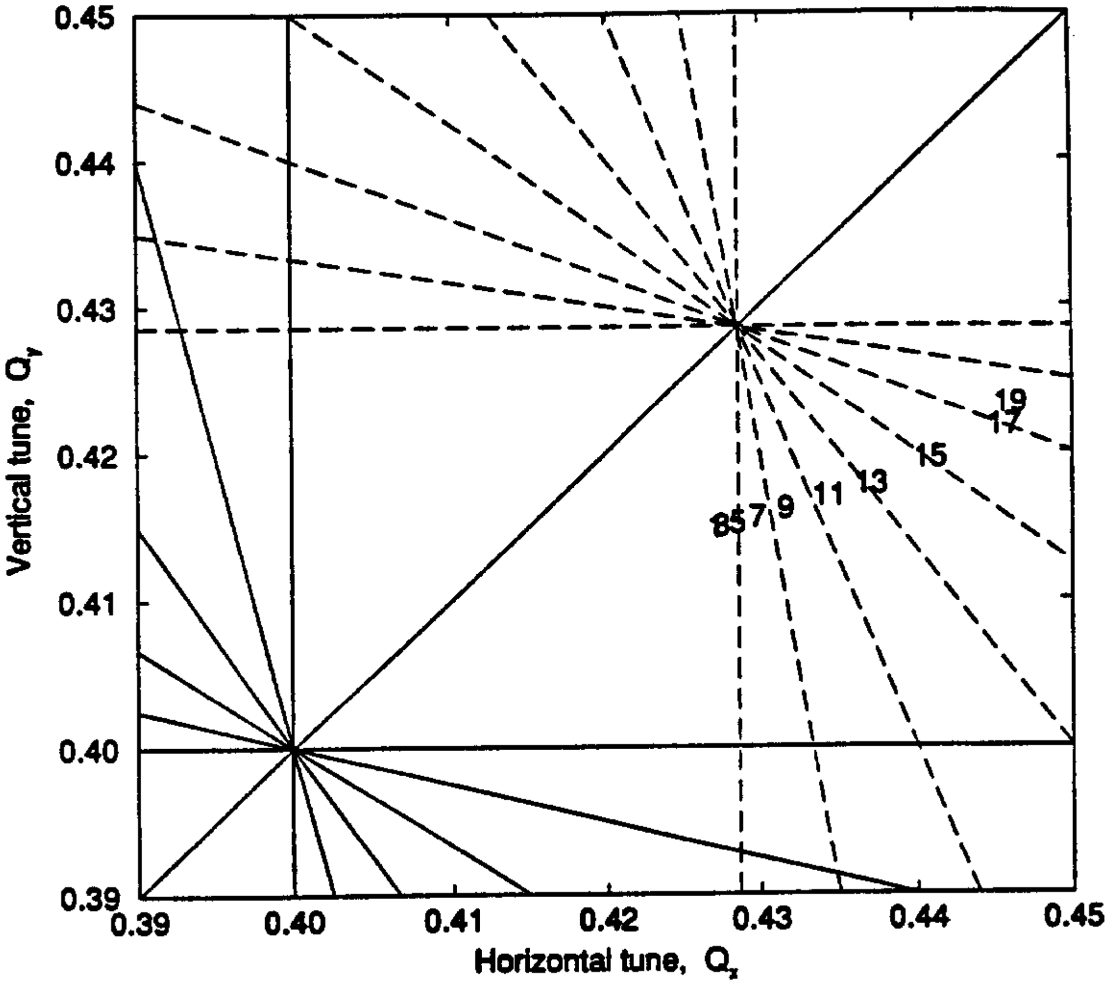

Fig. 3 Tune tune plot, numbers on the plot 1 to 19 are the initial amplitude of the launched particle.

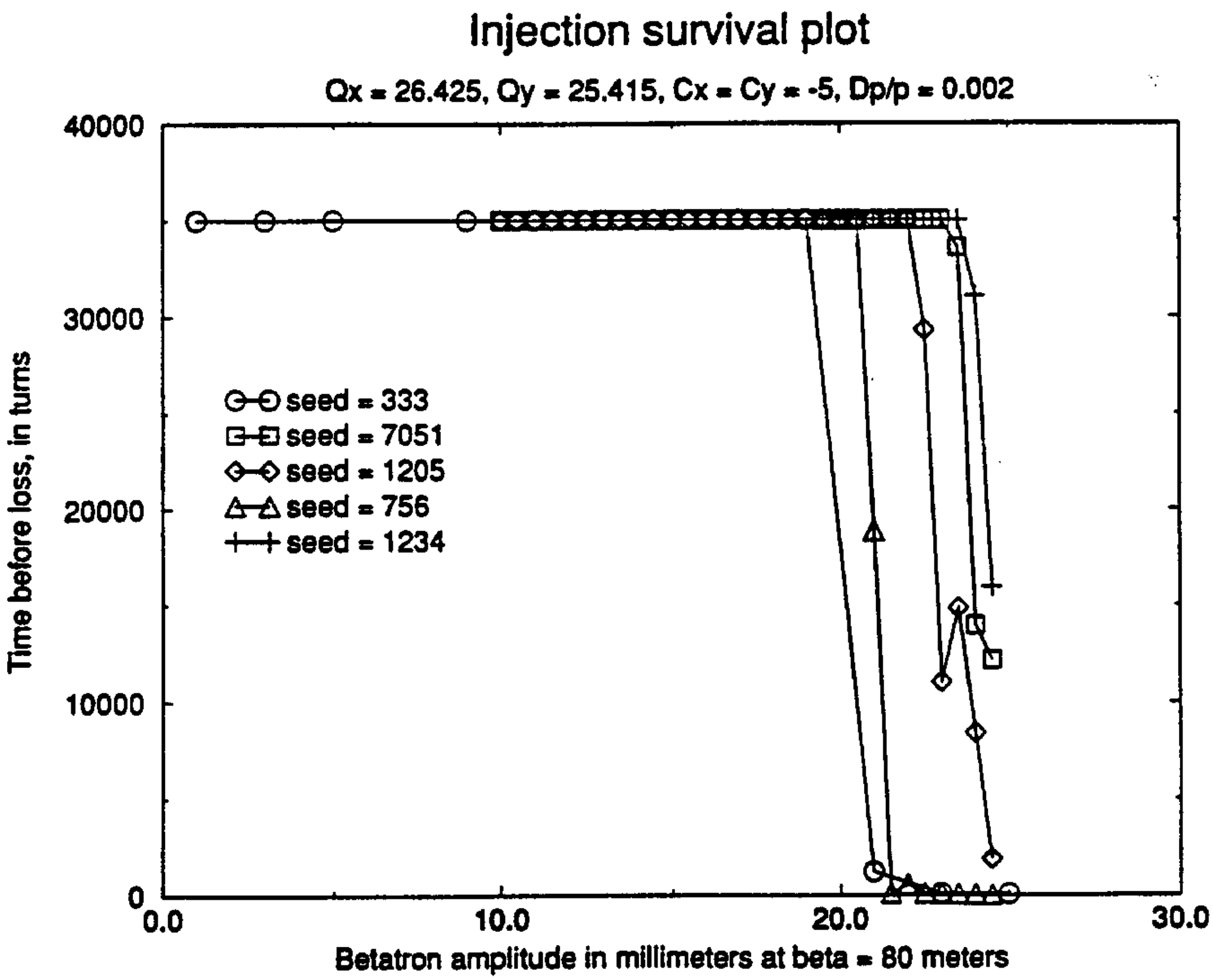

Fig. 4 Injection Survival plot for five seeds.

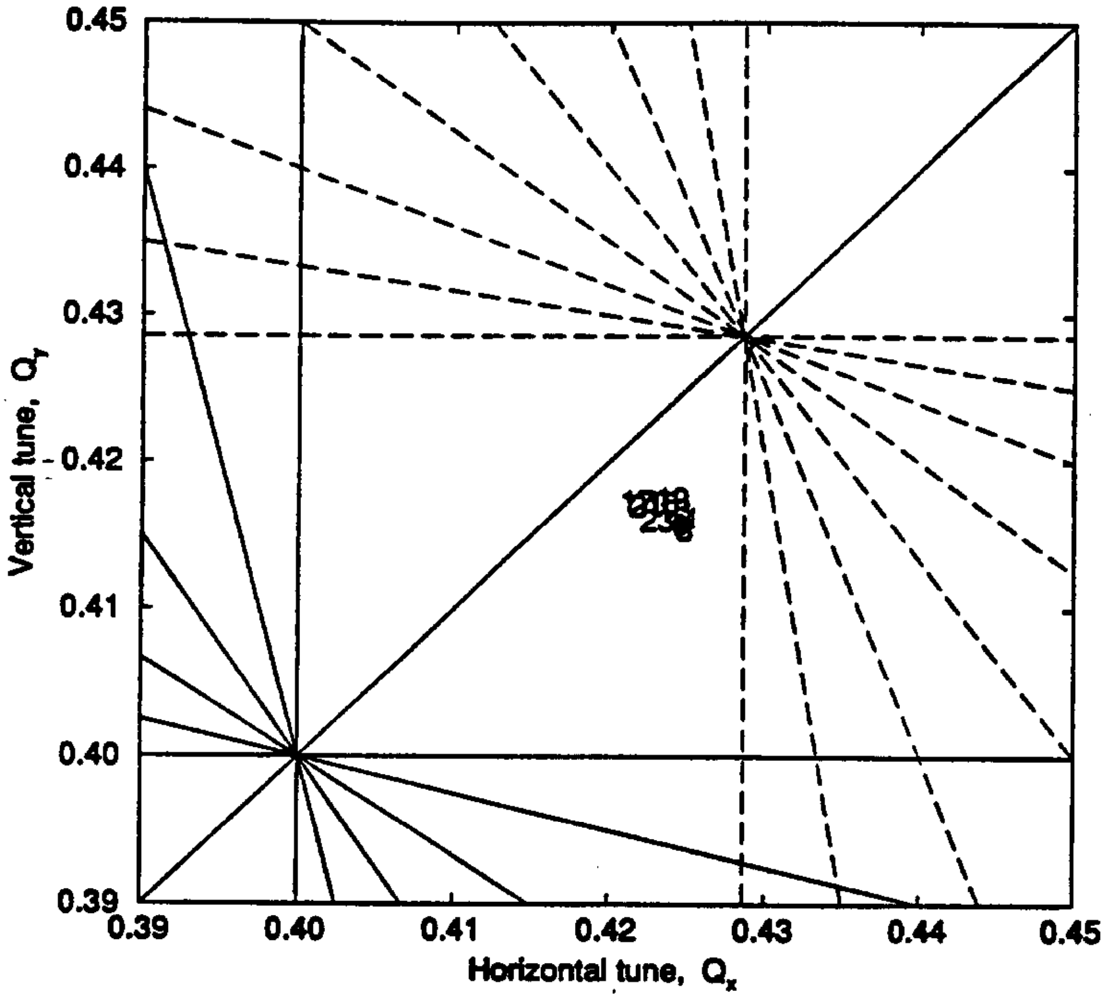

Fig. 5 Same as fig 5, but for half the nominal dipole end sextupole and no MR quads octupole.